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RAPIDLY DECAYING SUPERNOVA 2010X: A CANDIDATE ".Ia" EXPLOSION

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ABSTRACT

We present the discovery, photometric, and spectroscopic follow-up observations of SN 2010X (PTF 10bhp). This supernova decays exponentially with $\tau_d = 5$ days and rivals the current recordholder in speed, SN 2002bj. SN 2010X peaks at $M_r = -17$ mag and has mean velocities of 10,000 km s^{-1}. Our light curve modeling suggests a radioactivity-powered event and an ejecta mass of $0.16\,M_\odot$. If powered by Nickel, we show that the Nickel mass must be very small ($\approx 0.02\,M_\odot$) and that the supernova quickly becomes optically thin to γ-rays. Our spectral modeling suggests that SN 2010X and SN 2002bj have similar chemical compositions and that one of aluminum or helium is present. If aluminum is present, we speculate that this may be an accretion-induced collapse of an O-Ne-Mg white dwarf. If helium is present, all observables of SN 2010X are consistent with being a thermonuclear helium shell detonation on a white dwarf, a ".Ia" explosion. With the 1 day dynamic-cadence experiment on the Palomar Transient Factory, we expect to annually discover a few such events.

Key words: supernovae: general – supernovae: individual (SN2010X, SN2002bj) – surveys – white dwarfs

Online-only material: color figures

1. INTRODUCTION

Our present knowledge of cosmic explosions is arguably biased by the searches themselves. In particular, the cadence and depth of many supernova searches are designed to efficiently discover supernovae of type Ia (SNe Ia). A repeat visit to the sky on timescales of 5 days maximizes sky coverage and is still sufficient to catch SNe Ia on the rise. The brilliance of these events, peak absolute visual magnitude of −19, sets the sensitivity of the searches. Conversely, fainter events and those with a shorter characteristic lifetime are likely to be missed in such searches.

To illustrate the unexplored nature of this phase space, we plot the luminosity of optical transients versus their characteristic timescale (Figure 1). SNe Ia are confined to a narrow band (Phillips 1993) with decay timescales ranging from 12 days to 3 weeks. Classical novae span a large range of timescales albeit at considerably lower luminosities.

Figure 1 brings two white spaces to attention: the wide "gap" in luminosity between novae and supernovae, and the apparent paucity of luminous events on short timescales.

Next, we discuss currently known exemplars of "faint" (i.e., lower luminosity than SNe Ia) and "fast" (i.e., faster than SN 2007ax) transients. SN 2005E occurred in the halo of its host galaxy and has been proposed as a helium detonation on a binary white dwarf (Perets et al. 2010b). SN 2005cz has been proposed to have a massive star origin (Kawabata et al. 2010). SN 2008ha is also being widely debated both as a deflagration of a white dwarf (Foley et al. 2009, 2010) and core-collapse of a massive star (Valenti et al. 2009).

Until recently, the fastest event known was SN 2002bj (Poznanski et al. 2010). It decayed by one magnitude in 5 days and was quite spectroscopically peculiar. The origin of this event is not yet clear.

The Palomar Transient Factory[17] (PTF) was motivated in great measure to systematically explore the phase space for fast and faint explosive transients (Law et al. 2009; Rau et al. 2009). Here, we present the discovery of a fast event, SN 2010X (PTF 10bhp).

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[17] http://www.astro.caltech.edu/ptf

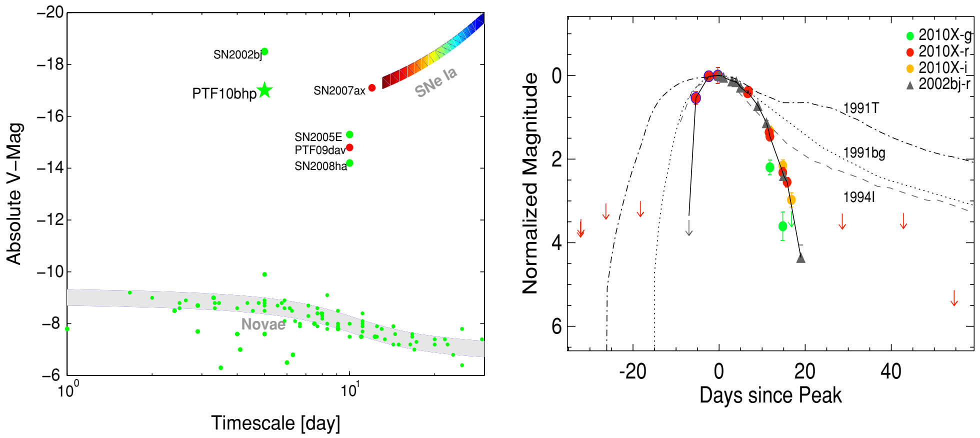

Figure 1. Left: phase space of cosmic explosive transients. The color for each event represents the color at peak brightness. The band to the top right denotes supernovae of type Ia. The fastest such event is SN 2007ax (Kasliwal et al. 2008). Classical novae occupy a band between −6 and −10 mag. Note that the only two transients with a timescale shorter than 10 days are SN 2010X (PTF 10bhp) and SN 2002bj. Right: the multi-band optical light curve of SN 2010X (colored circles; green is *g* band, red is *r* band, orange is *i* band). Three white-light measurements have been calibrated to *r* band and denoted by red circles with blue outline. Downward arrows represent upper limits. All light curves are normalized and shifted so that the peak magnitude is zero and the time at peak is set to zero. For SN 2010X, the epoch of maximum light is at MJD of 55239.5. The fast evolution of SN 2010X is compared to the current recordholder for fast supernovae, SN2002bj (gray triangles; *r* band; Poznanski et al. 2010). Also shown is a prototypical "fast" Type Ic supernova, SN1994I (dashed line; Richmond et al. 1996) and templates (http://supernova.lbl.gov/∼nugent/nugent_templates.html) of the fast Type Ia SN1991bg and slow Type Ia SN1991T (Nugent et al. 2002). Note the rapid rise and the spectacular decay of SN 2010X and SN 2002bj relative to the other Type I exemplars.

(A color version of this figure is available in the online journal.)

2. DISCOVERY

On UT 2010 February 7.07, D. Rich of Hampden, Maine discovered a transient in the galaxy NGC 1573A at R.A.(J2000) = $04^{\mathrm{h}}48^{\mathrm{m}}27^{\mathrm{s}}.7$ and decl.(J2000) = $+73^{\circ}28'13''$. The discovery was confirmed by P. Burke of Pittsfield, Maine, upon which a notification was issued (CBET 2166; Rich & Burke 2010) and the transient dubbed SN2010X. On UT 2010 February 19.13, the PTF independently detected this same transient and the pipeline assigned the name, PTF 10bhp. PTF had previously undertaken observations of this field (as a part of the dynamic-cadence experiment) on January 11, 17, and 25 but with no detection.

3. OPTICAL LIGHT CURVE

Energized by the apparent rapid fading, we initiated follow-up observations. The photometric observations from the 2 m Faulkes North Telescope (FTN) of the Las Cumbres Observatory Global Telescope (LCOGT), PTF, the Palomar Hale 200 inch telescope (P200) as well as white-light observations provided by our amateur astronomer colleagues are summarized in Figure 1.

SN 2010X is located close to the nucleus of its host galaxy ($4''.4$E, $6''.0$N) and as such galaxy light subtraction is critical to produce reliable photometry. The images were subtracted from a template image using the software `hotpants` and `wcsremap` to measure a convolution kernel and align the images, respectively (both codes supplied by A. Becker[18]). Aperture photometry was performed on each of these in a self-consistent manner using the same set of 22 calibration stars. Conversions from USNO-B1 magnitudes to Sloan Digital Sky Survey (SDSS) gri magnitudes were done adopting Jordi et al. (2006). The resulting light curve is plotted in Figure 1.

Overplotting SN 2002bj, we find that light curves of the two supernovae are remarkably similar. Linearly fitting all the *r* band detections post-maximum light, we measure that SN 2010X decayed by 0.23 ± 0.01 mag day^{-1}. The corresponding exponential timescale (in the *r* band) is $\tau_d = 4.7 \pm 0.2$ days.

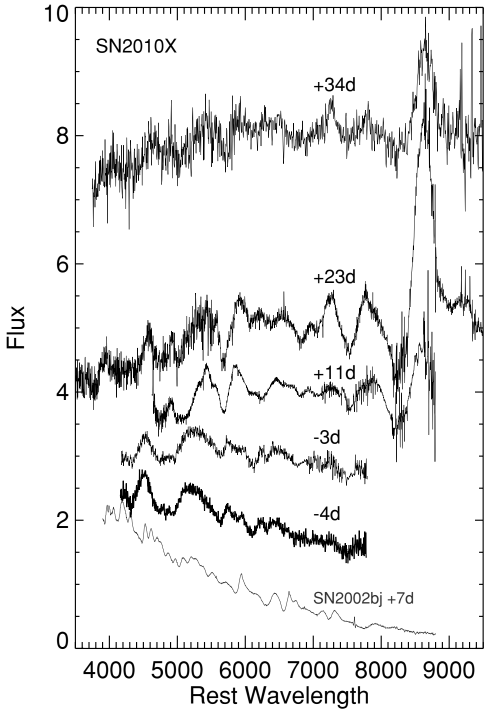

Figure 2. Spectroscopic follow-up of SN 2010X by MDM, *Gemini*, Keck, and Palomar Observatories. The phase of the spectra relative to maximum light is labeled. Note the velocity evolution. Also shown is a spectrum of SN 2002bj (Poznanski et al. 2010).

The foreground Galactic extinction along the line of sight is $E(B-V) = 0.146$ or $A_r = 0.4$ (Schlegel et al. 1998). The redshift of NGC 1573A is 0.015. Assuming standard cosmology (and $h_0 = 0.72$), we adopt a distance of 62.5 Mpc and a distance modulus of 34.0. Thus, the peak absolute magnitude of SN 2010X is $M_r \approx -17.0$ mag, 1.5 mag less luminous than SN2002bj.

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[18] http://www.astro.washington.edu/users/becker/c_software.html

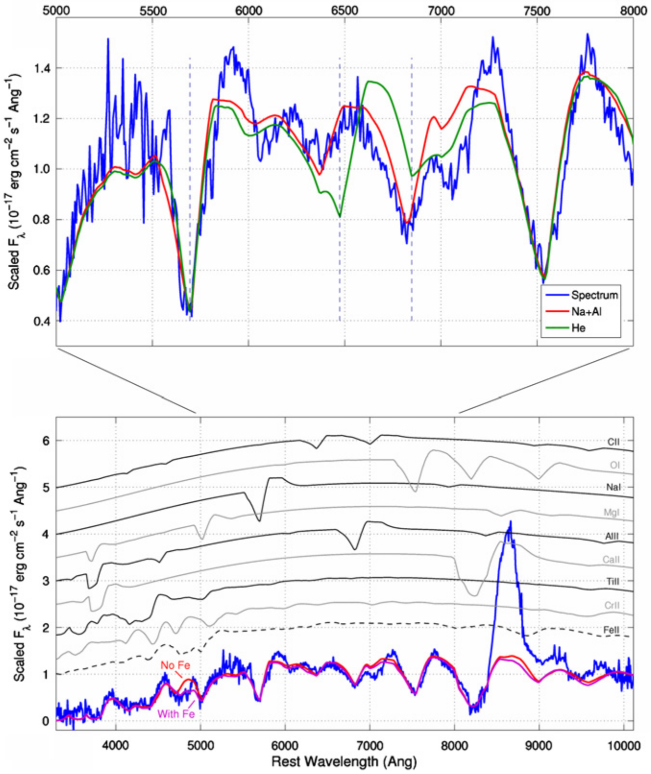

Figure 3. SYNOW fit to the Keck spectrum (+23 days) of SN 2010X. Lines contributed by each ion are shown. Fits with (purple) and without (red) iron are overplotted on the data (blue). Top panel: the dilemma of whether SN 2010X has helium or a combination of sodium and aluminum. The vertical dashed lines show helium at 9500 km s^{-1}. In non-LTE, the singlet transition of λ6678 may be suppressed relative to the λ7065 and λ5876 triplet transition helium lines.

(A color version of this figure is available in the online journal.)

4. SPECTROSCOPIC FOLLOW-UP

On February 8 and 9, the first spectra (Figure 2) to classify the nature of this transient were taken with CCDS on the 2.4 m Hiltner telescope of the MDM observatory (CBET 2167; Milisavljevic & Fesen 2010). Comparison with a library of supernova spectra using SNID (Blondin & Tonry 2007) showed resemblance to the Type Ic supernovae SN 1994I and SN 2004aw a few days before maximum light. Further observations (Figure 2) were undertaken on Gemini-North/GMOS (February 23), Keck I/LRIS (March 7), and the Hale 200 inch/DBSP (March 18) telescopes. No perfect matches to Ic (or Ia, Ib) templates were found for these spectra. The velocity evolved from 12,000 km s^{-1} before maximum to 9000 km s^{-1} at late time.

We used SYNOW (Jeffery & Branch 1990) to infer elements in the spectra of SN 2010X (Figure 3). The most prominent identifications are oxygen (O I lines), calcium (both Ca II IR triplet and Ca II H+K on the blue side), carbon (C II lines), titanium (Ti II), and chromium (Cr II). Ti II and Cr II explain the broad blue features, and adding Fe II improves the fit slightly. There is also some evidence for Mg I albeit based on single line.

The presence of helium (He I), sodium (Na D), and aluminum (Al II) is less clear, and we illustrate this dilemma in the inset of Figure 3. He I has three relevant lines: 5876 Å, 6678 Å, and 7065 Å . The absorption feature around 5700 Å can be explained by both He I as well as Na D. The absorption feature around 6850 Å can be explained by Al II or He I. Since the central He I line is not prominent, SYNOW suggests that the combination of Na D and Al II is a better fit. However, Branch (2003) discuss that this central He I line is a singlet transition and this may both be suppressed and blueshifted in non-LTE relative to the other two He I triplet transitions. Therefore, we cannot conclusively say whether or not helium is present in SN 2010X.

Comparing the spectra, SN 2002bj has substantially lower velocities (4000 km s^{-1} at +7 days versus 10,000 km s^{-1} at +10 days) and a bluer continuum ($g-r = 0.2$ at +12 days versus $g-r = 1.2$ at +23 days) than SN 2010X. Consistent with the SYNOW fit shown in Poznanski et al. 2010, the elements in common between the two supernovae are O I, C II, and Mg II. The primary difference is the presence of Ca II in SN 2010X and presence of S II in SN 2002bj. We re-fit the spectrum of SN 2002bj with the same elements as in SN 2010X. We find that the presence of Al II versus He I is just as ambiguous for SN 2002bj as SN 2010X. Similar to SN 2010X, including Fe II improves the fit but the presence of Fe-group elements in SN 2002bj is not conclusive.

5. MODELING THE LIGHT CURVE

The excellent match between the normalized light curves of SN 2010X and SN 2002bj (see Figure 1) suggests that these two supernovae belong to the same class of explosions. Combining the two data sets allows a robust determination of the rise time[19] ($\tau_r \approx 6$ days) and the subsequent exponential decay ($\tau_d \approx 5$ days).

The peak bolometric luminosity of SN 2010X is $L_{\rm peak} = 10^{42}$ erg s^{-1}. While the expansion speed varies from 12,000 km s^{-1} at early times to 9000 km s^{-1} at late times, we accept $v_s \approx 10{,}000$ km s^{-1} as a representative value.

The rise time in an explosion is the geometric mean of the initial photon diffusion timescale and the initial hydrodynamic timescale.[20] Thus, $\tau_r{}^2 \propto \kappa M_{\rm ej}/v_s$, where κ is the opacity. Assuming that the mean opacity of SN 2010X is the same as that for SNe Ia events (for which, following Hayden et al. 2010, we adopt the following: $M_{\rm ej} \approx 1.4\,M_\odot$, $v_s = 10^9$ cm s^{-1}, and $\tau_r \approx 17.5$ days), we obtain $M_{\rm ej} \approx 0.16\,M_\odot$. This gives an explosion energy, $E_0 = 1/2 M_{\rm ej} v_s^2 \approx 1.7 \times 10^{50}$ erg.

Next, we investigate a physical model that satisfactorily accounts for the rise time, the decay time, the peak luminosity, and the expansion velocity.

5.1. *Pure Explosion*

The simplest model is an explosion in which all the explosive energy (E_0) is deposited instantaneously into the ejecta. The peak luminosity is then $E_0/t_d(0)$, where $t_d(0) \propto \kappa M_{\rm ej}/R_0$ is the initial photon diffusion time; here, R_0 is the radius of the progenitor. Following peak luminosity, the decay is rapid: $\log(L) \propto -(t/\tau_r)^2$. The virtue of this model is that one can obtain an arbitrarily rapid rate of decay since, over any limited stretch of time, the light curve can be approximated by a linear decay with the desired value for the slope.

For SN 2010X, we find $R_0 \sim 4 \times 10^{12}$ cm. The large inferred radius would make sense if the progenitor had an envelope (as in type II supernovae). The absence of hydrogen at any phase of the supernova (see Section 4) argues strongly against this model. Hence, we reject this hypothesis.

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[19] Time from explosion to peak brightness.

[20] The derivation can be found in the textbooks, Arnett (1996) and Padmanabhan (2001).

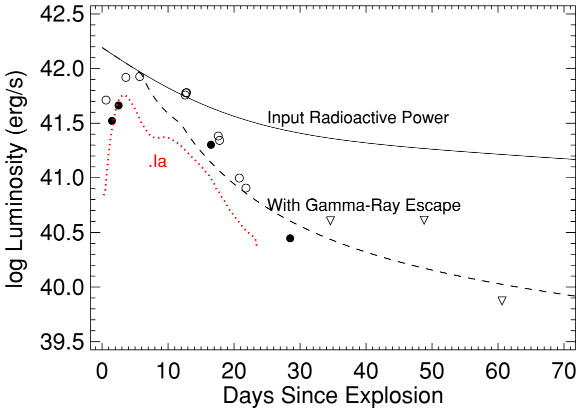

Figure 4. Shown above is the radioactive luminosity (solid line) and absorbed luminosity (dashed line) for the following model parameters: $M_{\rm ej} = 0.16\,M_\odot$, $M_{\rm Ni} = 0.02\,M_\odot$, and $v = 10^9$ cm s^{-1}. Also shown is a quasi-bolometric light curve of SN 2010X estimated by (a) computing νF_ν in r band (empty circles are detections and inverted triangles are upper limits), and (b) integrating the optical spectrum (filled circles). Also shown is a comparison to a “.Ia” light curve (red dotted line; Shen et al. 2010) assuming: $M_{\rm wd} = 1.2\,M_\odot$, $M_{\rm env} = 0.02\,M_\odot$, $M_{\rm ej} = 0.017\,M_\odot$, $M_{\rm Fe} = 0.003\,M_\odot$, $M_{\rm Ni} = 0.002\,M_\odot$, $M_{\rm Cr} = 0.001\,M_\odot$.

(A color version of this figure is available in the online journal.)

5.2. *Radioactivity-powered Explosion*

The next level of models is that developed for SNe Ia explosions, where the peak luminosity and subsequent decay is governed by radioactive material present in the ejecta. In this model, expansion decreases the store of internal energy whereas radioactivity increases it. If the photon diffusion timescale is long, most of the radioactive energy goes into expansion. Once the diffusion timescale becomes smaller than the expansion timescale, the light curve tracks the radioactive luminosity (Arnett 1982), provided that there is sufficient optical depth for the γ-rays emitted during radioactive decay to undergo multiple scatterings and lose their energy to electrons.

The primary source of luminosity in an SN Ia model is the heat provided by γ-rays emitted as ^{56}Ni decays to ^{56}Co and then to ^{56}Fe. In SNe Ia, the column density of the ejecta is thick enough to trap the γ-rays and successive Compton scatterings extract energy from the γ-rays (at least for the first month). However, given the small ejecta mass for SN 2010X, attention has to be paid to the possibility that γ-rays from decaying nuclei may escape without depositing their energy into the ejecta.

The electron (Thompson) optical depth is

$$\tau_e = n_e R \sigma_T = \frac{3}{4\pi}\frac{M_{\rm ej}}{m_p}\frac{Z}{A}\frac{\sigma_T}{R^2}$$
$$\sim 9\left(\frac{M_{\rm ej}}{0.16\,M_\odot}\right)\left(\frac{t}{15\,\rm day}\right)^{-2}, \qquad (1)$$

where Z is the atomic number, A is the mass number, m_p is mass of proton, σ_T is the Thompson cross-section, and $R \sim 6(t/\text{day})$ AU is the radius at time t.

Thus, there appears to be sufficient optical depth at the epoch of peak luminosity to trap most of the γ-rays. Thus, for SN 2010X, the peak luminosity of 10^{42} erg s^{-1} corresponds to ^{56}Ni mass of about $0.02\,M_\odot$—a very small amount by the standards of most supernovae. For SN 2002bj, the peak luminosity was 10^{43} erg s^{-1} (Poznanski et al. 2010) and the inferred ^{56}Ni mass was correspondingly larger, $0.2\,M_\odot$.

Next, we use a fitting formula (as given in Kulkarni 2005, Equation (47)) to estimate the fraction of γ-rays which are effectively absorbed inside the ejecta, $\eta(\tau_e)$. The kinetic energy of positrons (3.5% of $L_{\rm Co}$; Sollerman et al. 2002) dominates by day 51. Hence, the radiated luminosity, $L_{\rm rad} = (0.965\eta + 0.035)L_{\rm Co} + \eta L_{\rm Ni}$, where $L_{\rm Ni}$ is the radioactive power released by the decay of ^{56}Ni and $L_{\rm Co}$ by the daughter ^{56}Co. In Figure 4, we display the luminosity due to radioactivity and that actually trapped in the ejecta—the latter shows a satisfactory agreement with the observations.

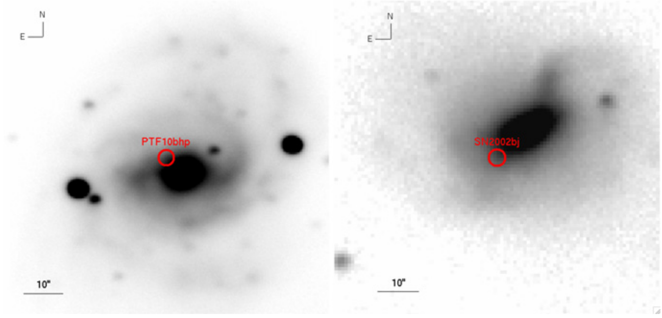

Figure 5. Left: R-band image of NGC 1573A, the host of SN 2010X, taken with the Large Format Camera on the Palomar 200 inch telescope. Right: sum of all available Deepsky (Nugent 2009; we note that the six photons in the XRT HPD PSF of 0.″3 are likely from the galaxy nucleus) images of NGC1821, the host of SN2002bj.

(A color version of this figure is available in the online journal.)

5.2.1. *Possible X-ray Signature*

An optically thin ejecta opens up the possibility of detecting the γ-rays (or degraded hard X-rays) emitted during β-decay. The *Swift* Observatory observed SN 2010X for 9758.7 s on MJD 55248.775 (9 days past peak). We constrain the X-ray flux to be less than 0.00050 counts s^{-1} or 7.7×10^{39} erg s^{-1}. By this epoch, our model shows that $L_\gamma \sim 10^{41}$ erg s^{-1}. Since photon number is conserved in scattering, the luminosity in the *Swift* band is expected to be a factor of 200 smaller and hence, the upper limit is not constraining.

6. ENVIRONMENT

The host of SN 2010X, NGC 1573A, is a small (1.″6 diameter), spiral galaxy variously classified as Sb (UGC) and SABbc (RC3). The host of SN 2002bj, NGC 1821, is a small (1.″1 diameter), barred irregular galaxy classified as IB(s)m. Both transients occurred close to the galaxy nucleus—2.3 kpc for SN 2010X and 1.8 kpc for SN 2002bj. In Figure 5, we show the location of the supernovae in deep images of the galaxy.

7. CONCLUSION

To summarize, SN 2010X is the second member of a class of supernovae that declines exponentially on timescales shorter than 5 days. Relative to SN 2002bj, SN 2010X is less luminous by 1.5 mag ($M_R \approx -17$) and has higher velocities (10,000 km s^{-1}) by more than a factor of two. Both events have a small inferred ejecta mass. Both events are spectroscopically different from any other type I supernovae. The spectra for both supernovae can be modeled with mostly similar elements (C, O, Mg, Si, Ti, and Fe). The evidence (or lack thereof) for helium is not conclusive in both cases.

If SN 2010X is powered by radioactive ^{56}Ni, the combination of a rapid rise time and low peak luminosity constrains the Nickel mass to be small, $0.02\,M_\odot$. ^{56}Ni constitutes ≈13% of ejecta. However, under the same assumptions, ^{56}Ni would constitute bulk of the ejecta mass for SN 2002bj. Thus, while in both cases the ejecta mass remains the same, the nucleosynthesis may be strongly variable. We also show that given the small ejecta mass, γ-rays from decaying ^{56}Ni can start escaping from the ejecta shortly after peak brightness. This early escape reasonably accounts for the rapid decay of the light curve of SN 2010X.

Perets et al. (2010a) have argued that S Andromeda (the first recorded SN in Andromeda) and SN 1939B (the first recorded SN in Virgo) are also like SN 2002bj. The claim primarily rests on rapid rise and rapid decay at early time. It is of some interest to note that the late-time (2 months to nearly 1 year) decay rates, 0.03 mag day^{-1} for S Andromeda and 0.02 mag day^{-1} for SN 1939B (Perets et al. 2010a), are consistent with ^{56}Co decay (with some escape of γ-rays). A consistent explanation would require a two-zone model: comparable amount of ^{56}Ni in a slowly expanding core (to account for the late time light curve) and a rapidly expanding shell (to account for the rapid decay seen after peak brightness).

An alternative model is that the early-time emission is powered by another suitably rapidly decaying radioactive element(s). If powered solely by ^{48}Cr, 0.02 $M_\odot$ is adequate. Recently, Shen et al. 2010 computed models and observables for ".Ia" explosions (Bildsten et al. 2007) powered by ^{48}Cr and ^{52}Fe: rise time between 2 and 10 days, ejecta velocity between 9000 and 13,000 km s^{-1}, peak luminosity between 0.5 and 5 × 10^{42} erg s^{-1}, and presence of Ca II and Ti II in the spectra. The properties of SN 2010X are consistent with all these predictions. Specifically, the light curve model presented for a core mass of 1.2 $M_\odot$ and envelope mass of 0.02 $M_\odot$ is a reasonable match (Figure 4). Furthermore, Shen et al. 2010 also discuss that the presence of helium in the spectra may be a non-LTE effect.

If aluminum is indeed present in the spectra, the avenue for a speculative scenario opens up. Neither ^{26}Al nor ^{27}Al is a product of helium burning. Aluminum can be made via explosive burning of neon and/or carbon (Arnett & Bazan 1997; Woosley & Weaver 1980). Perhaps, SN 2010X is the outcome of accretion-induced collapse of an O-Ne-Mg white dwarf (Metzger et al. 2009).

Finally, we note that the rich, star-forming environment of SN 2010X and SN 2002bj does not preclude a massive star origin. Fallback events, where a massive star collapses into a black hole, are also expected to be fast declining (Fryer et al. 2009; Moriya et al. 2010). However, the velocities expected from these models are significantly lower than observed and the spectra are more substantially dominated by intermediate mass elements.

Regardless of all these rich possibilities, it is clear that further progress in understanding the nature of these ephemeral transients would require a larger sample. Fortunately, PTF, especially as it moves to "dynamic" 1 day cadence (Law et al. 2009) targeting nearby galaxies and clusters, is well equipped to annually find a few such events. Late-time photometry is important to look for tell-tale signatures of ^{56}Co decay. Sensitive optical (or better still, ultraviolet) spectroscopy may directly reveal the radioactive element(s) powering these events. It is also not inconceivable (given the history of S Andromeda and SN 1939B) that we will be lucky enough to observe a local analog of such an event with the hard X-ray mission, NuSTAR (Harrison et al. 2010).

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Facilities: PO:1.2m, Hale, Gemini:Gillett, Hiltner, Swift

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